

# MSC Nastran Topology Optimization

## - Minimizing mass with stress and displacement constraints

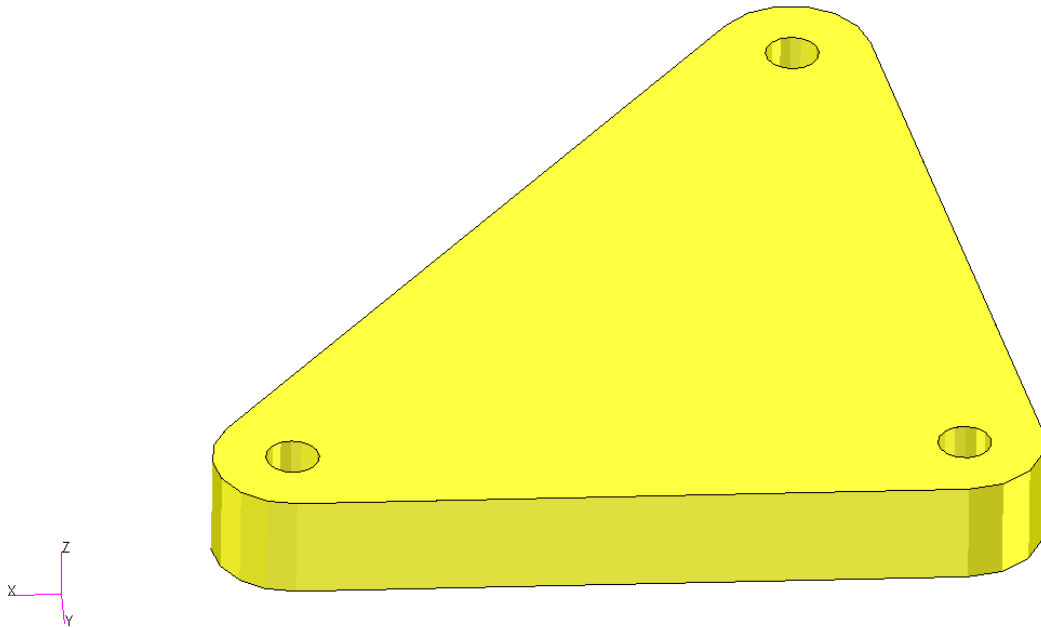
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PRESENTED BY CHRISTIAN APARICIO

# Goal: Use Nastran SOL 200 Optimization

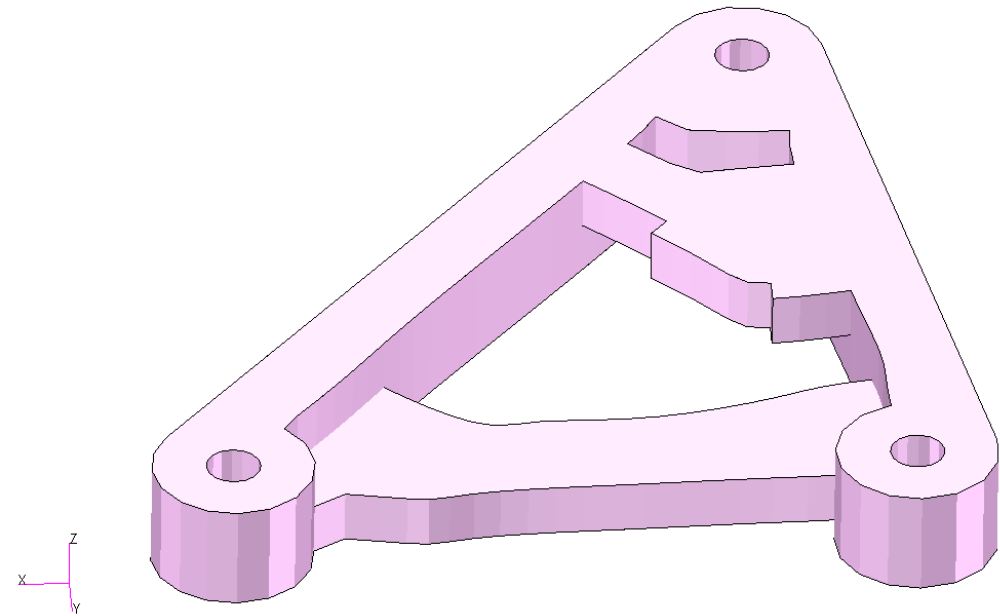
## Before Optimization

- Mass: 18 kg



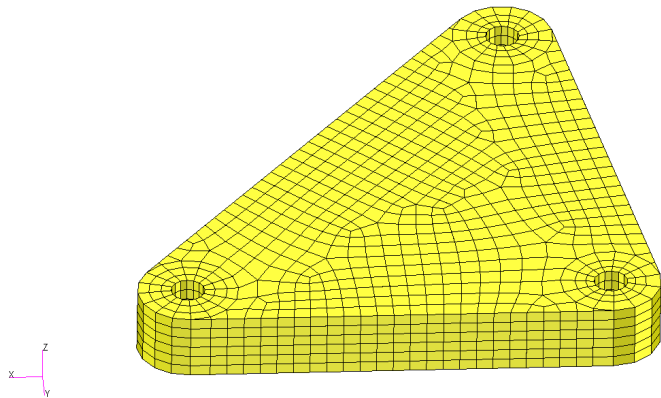
## After Optimization

- Mass: 9.3 kg
- Prevent excessive stress and displacements

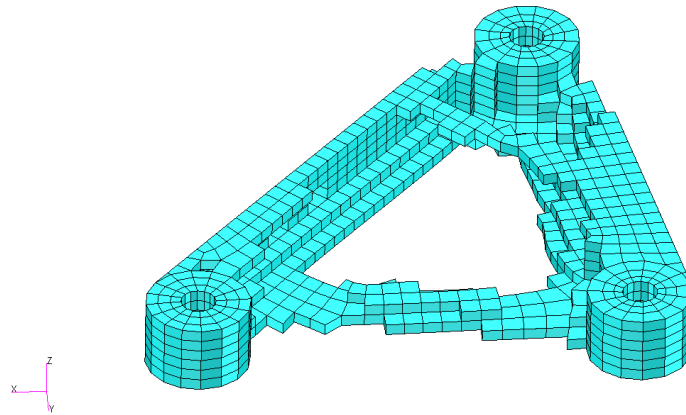


# Goal: Use Nastran SOL 200 Optimization

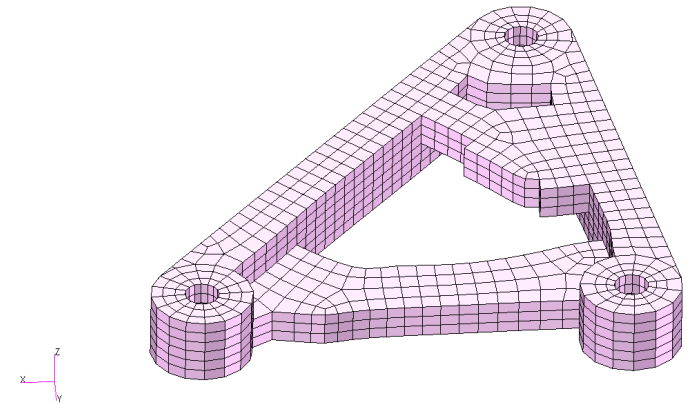
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1) Initial Design



2) Proposed Topology Solution



3) Final Design

# Agenda

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Details of the structural model

Optimization Problem Statement

Steps to use Nastran SOL 200 (Optimization)

- Convert a .bdf file to SOL 200
- Create:
  - Design Regions/Variables
  - Design Objective
  - Design Constraints
- Perform optimization with Nastran SOL 200

View optimization results

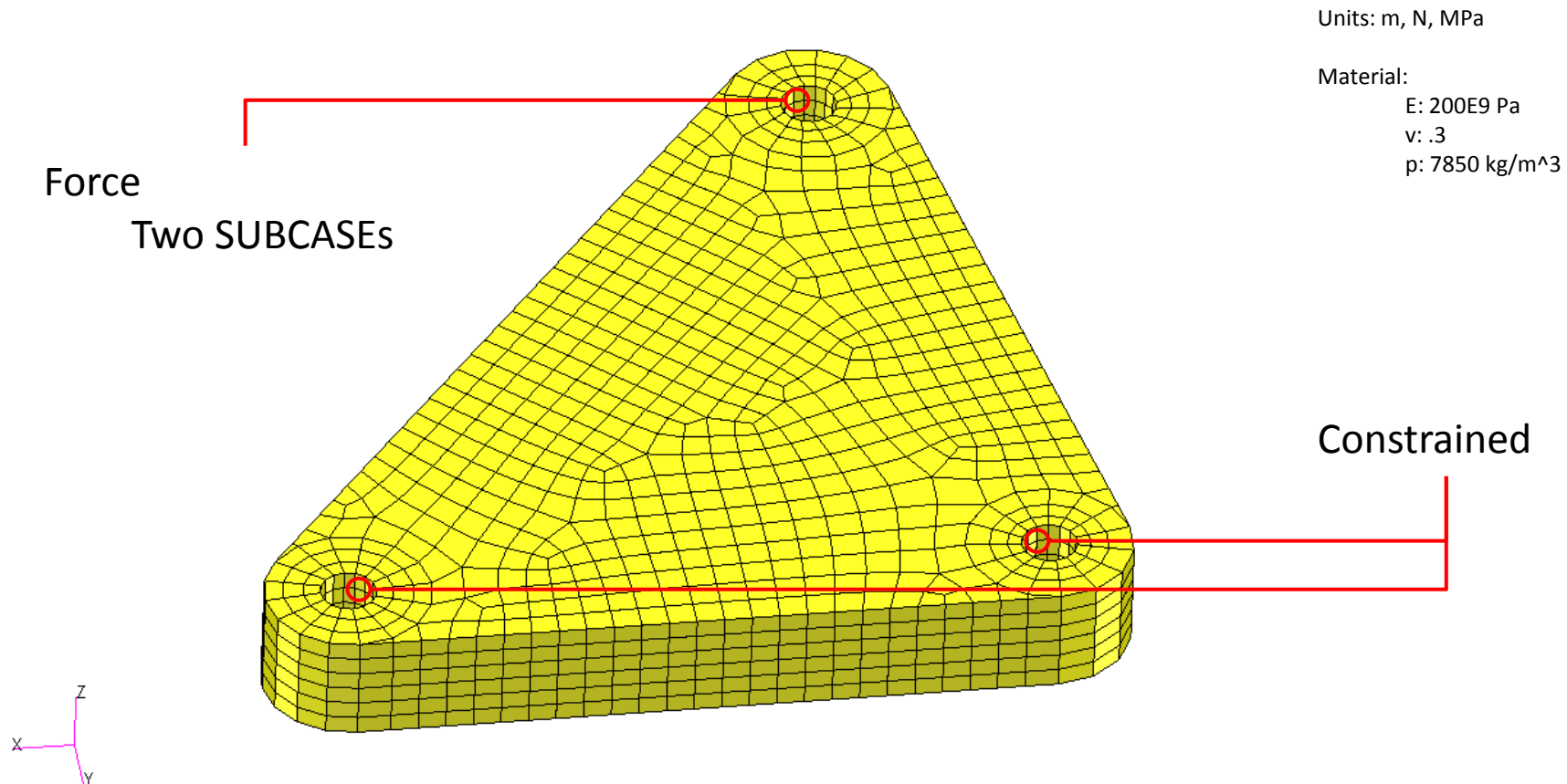
- Online Plotter
- Topology Optimization and Structural Results

# Contact me

- Nastran SOL 200 training
- Nastran SOL 200 questions
- Structural or mechanical optimization questions
- Access to the SOL 200 Web App

christian@ the-engineering-lab.com

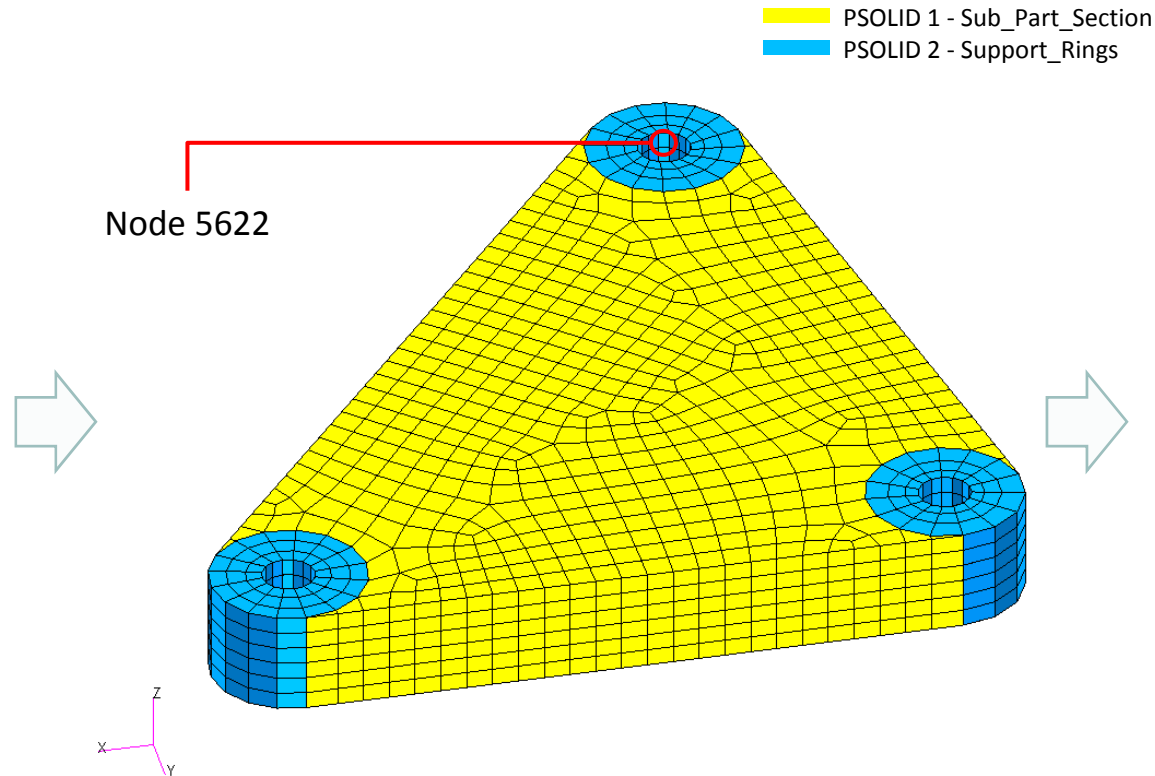
# Details of the structural model



# Optimization Problem Statement

## Design Region/Variables

x1: PSOLID 1



## Design Objective

r0: Minimize fractional mass (FRMASS)

## Design Constraints

r1: Z displacement at node 5622 (GRID 5622)

$$r1 < .0008 \text{ m}$$

x1: Maximum allowable stress, 2.0E8 Pa, on design region x1

# Steps to use Nastran SOL 200 (Optimization)

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1. Start with a .bdf or .dat file
2. Use the SOL 200 Web App to:
  - Convert the .bdf file to SOL 200
    - Design Regions/Variables
    - Design Objective
    - Design Constraints
  - Perform optimization with Nastran SOL 200
3. Review optimization results
  - Online Plotter
  - Topology Optimization and Structural Results



# SOL 200 Web App Capabilities

The Post-processor Web App and HDF5 Explorer are free to MSC Nastran users.

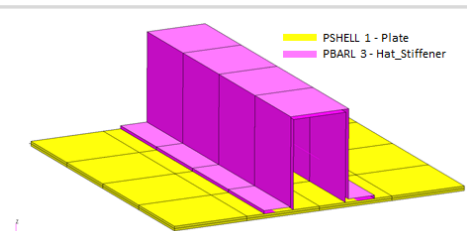
## Compatibility

- Google Chrome, Mozilla Firefox or Microsoft Edge
- Windows and Red Hat Linux
- Installable on a company laptop, workstation or server. All data remains within your company.

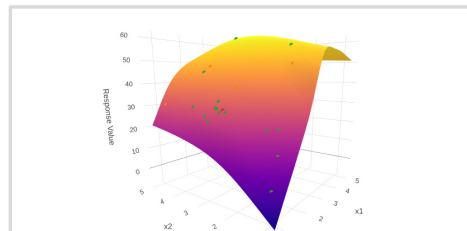
## Web Apps

## Benefits

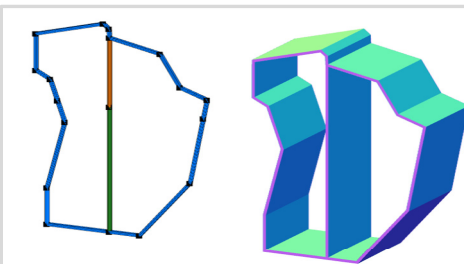
- REAL TIME error detection. 200+ error validations.
- REAL TIME creation of bulk data entries.
- Web browser accessible
- Free Post-processor web apps
- +80 tutorials



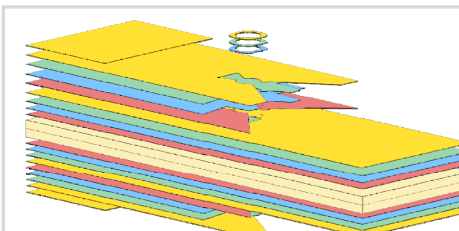
**Web Apps for MSC Nastran SOL 200**  
Pre/post for MSC Nastran SOL 200.  
Support for size, topology, topometry, topography, multi-model optimization.



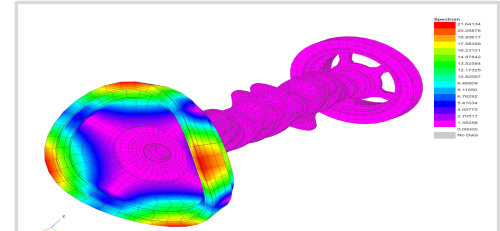
**Machine Learning Web App**  
Bayesian Optimization for nonlinear response optimization (SOL 400)



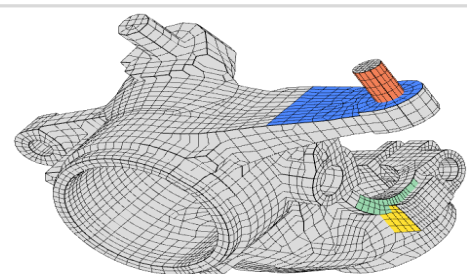
**PBMSECT Web App**  
Generate PBMSECT and PBRSECT entries graphically



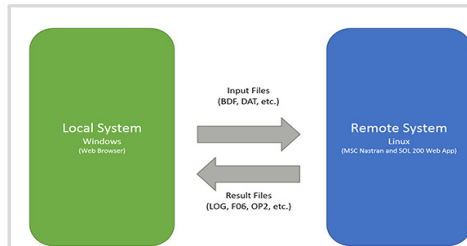
**Ply Shape Optimization Web App**  
Optimize composite ply drop-off locations, and generate new PCOMPG entries



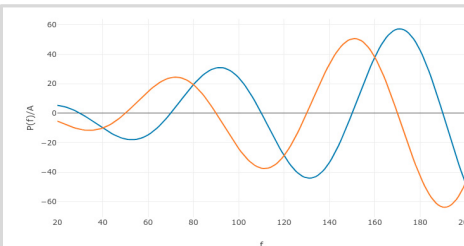
**Post-processor Web App**  
View MSC Nastran results in a web browser on Windows and Linux



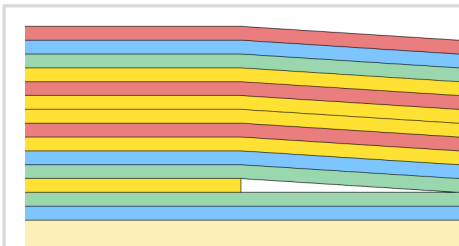
**Shape Optimization Web App**  
Use a web application to configure and perform shape optimization.



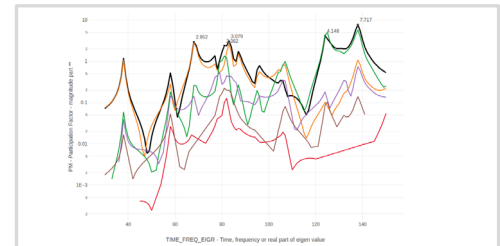
**Remote Execution Web App**  
Run MSC Nastran jobs on remote Linux or Windows systems available on the local network



**Dynamic Loads Web App**  
Generate RLOAD1, RLOAD2 and DLOAD entries graphically



**Stacking Sequence Web App**  
Optimize the stacking sequence of composite laminate plies



**HDF5 Explorer Web App**  
Create graphs (XY plots) using data from the H5 file

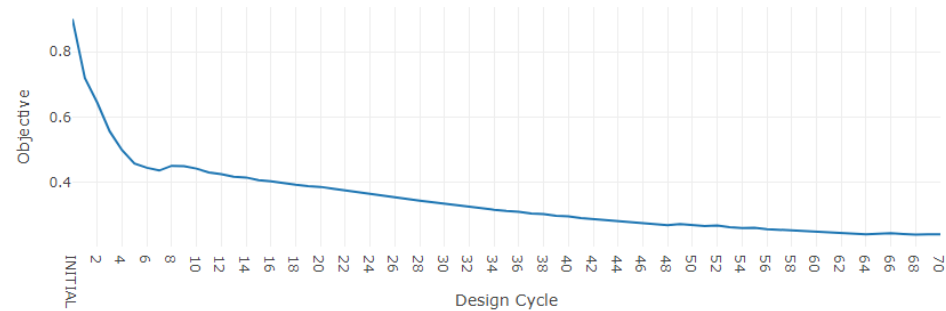
# View Optimization Results

## Online Plotter

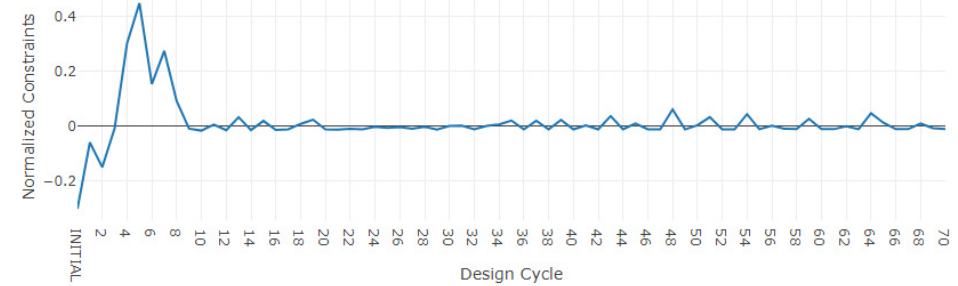
Final Message in .f06

✓ RUN TERMINATED DUE TO HARD CONVERGENCE TO AN OPTIMUM AT CYCLE NUMBER = 70.

Objective



Normalized Constraints



# Contact me

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- Access to the SOL 200 Web App

christian@ the-engineering-lab.com

# Topology Optimization Workflows

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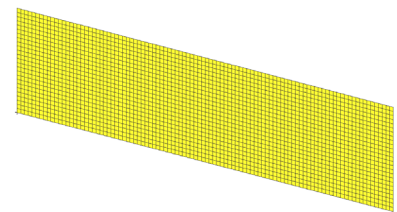
# Traditional Topology Optimization

Objective: Minimize Compliance (Maximize Stiffness)

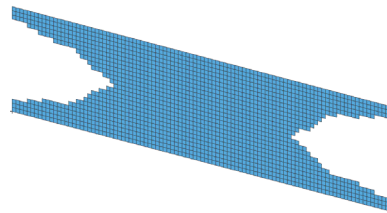
Constraint: Fractional Mass < .## (Target Mass)

---

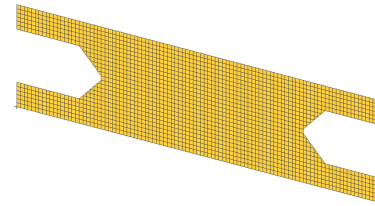
Original Design



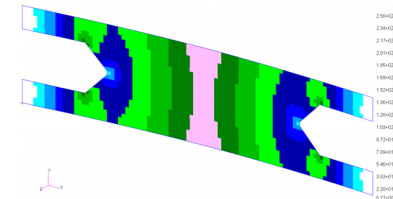
Mass: 9.737 grams



FRMASS < .75  
Mass: 7.186 g  
Optimization B



Mass: 7.739 g



Max von Mises: 150 MPa  
Max Displacement : 2.78 mm

1<sup>st</sup> natural Frequency: 111 Hz

# Traditional Topology Optimization

Objective: Minimize Compliance (Maximize Stiffness)

Constraint: Fractional Mass < .## (Target Mass)

## Topology Solution

## Refined Design

## Verification

### Original Design

Mass: 9.737 grams

FRMASS < .9  
Mass: 8.756 g  
Optimization A

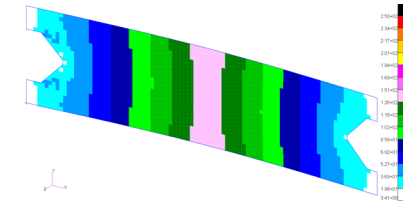
FRMASS < .75  
Mass: 7.186 g  
Optimization B

FRMASS < .6  
Mass: 5.718 g  
Optimization C

Mass: 9.094 g

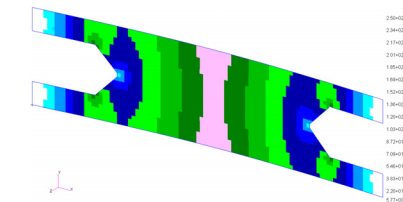
Mass: 7.739 g

Mass: 6.119 g



Max von Mises: 150 MPa  
Max Displacement: 2.52 mm

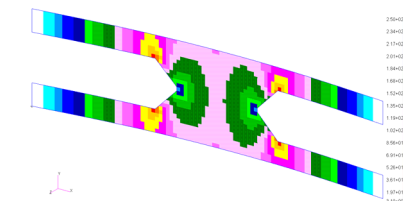
1<sup>st</sup> natural Frequency: 114 Hz



Max von Mises: 150 MPa  
Max Displacement : 2.78 mm

1<sup>st</sup> natural Frequency: 111 Hz

Optimization B led to a valid  
and light weight design



Max von Mises: 250 MPa  
Max Displacement : 3.57 mm

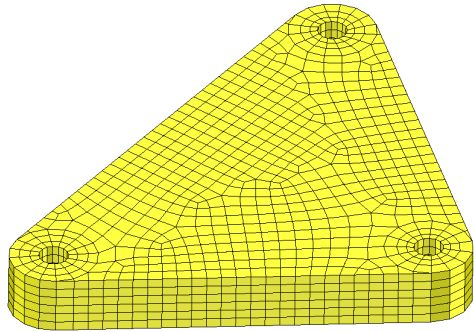
1<sup>st</sup> natural Frequency: 109 Hz

# Latest Topology Optimization

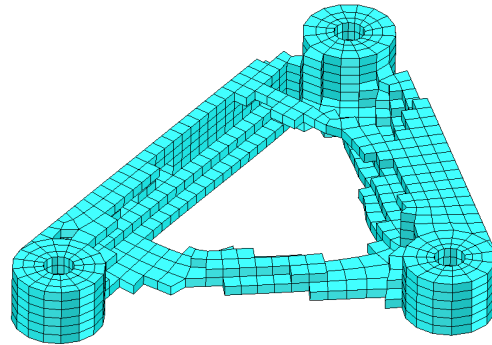
Objective: Minimize Fractional Mass (Minimize Mass)

Constraint: Stress Constraint

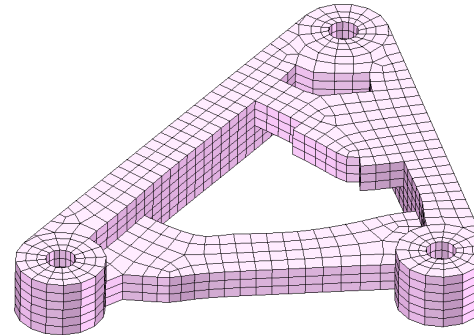
Original Design



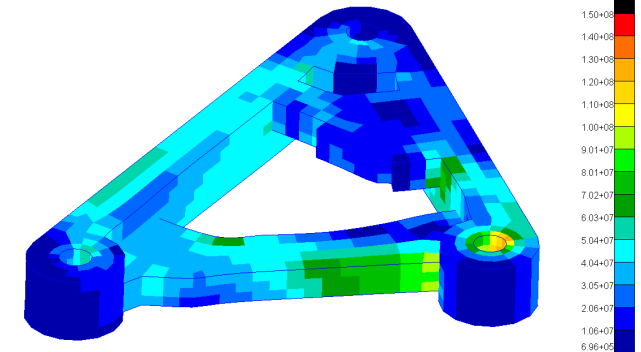
Topology Solution



Refined Design



Verification



# Appendix

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# Appendix Contents

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- Frequently Asked Questions
  - What are the design variables in Topology Optimization?
  - What is FRMASS or Fractional Mass?
  - What is compliance?
  - How can non-critical elements be removed from the design?

# What are the design variables in Topology Optimization?

Consider the following topology optimization workflow.

1. A topology design region is selected.
  - 1 material
  - 2048 elements
2. At the start of an optimization, each element is assigned its own material (stiffness and density).
  - 2048 materials
  - 2048 elements
3. During the optimization, each element is given a topology variable  $x_i$ , where  $i$  is the element ID.
  - 2048 topology variables

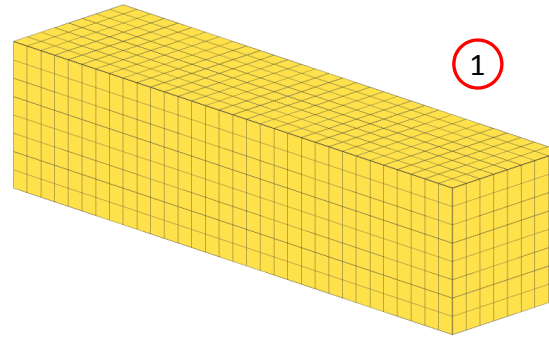
The topology variable  $x_i$  controls the material density and stiffness of element  $i$  via these expressions.

- $p_i = p_0 \cdot x_i$
- $E_i = E_0 \cdot x_i^{\text{Penalty}}$

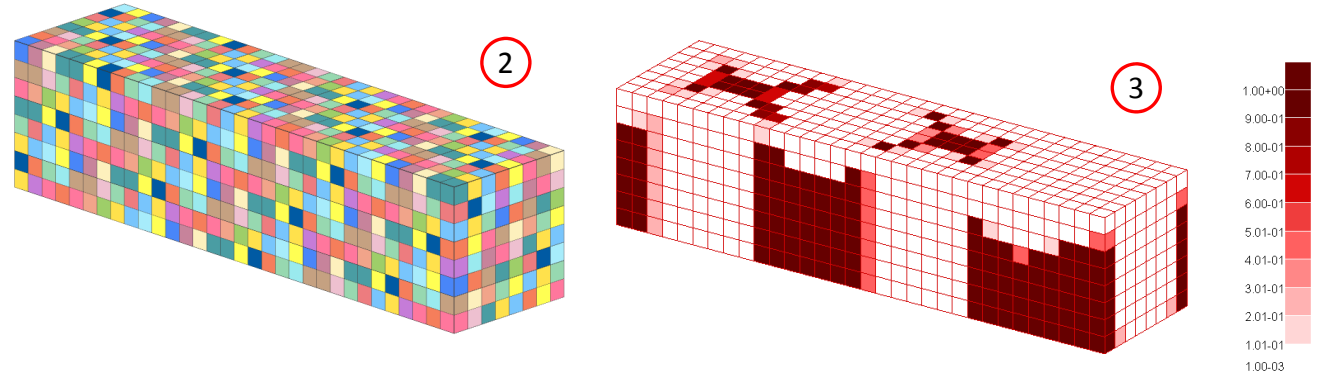
The penalty term ranges between 2-5 and is 3 by default. The topology variable varies between 0 and 1.

4. After the topology optimization, the user must decide which elements to keep.
  - During the topology optimization, elements are not automatically removed. It is up to the user to decide which elements to keep after the optimization.

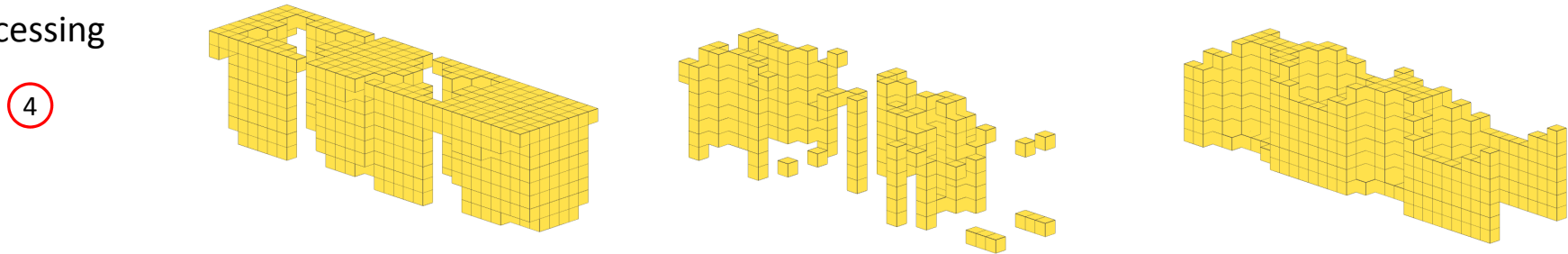
## Topology Design Region



## Topology Optimization



## Results Post-processing



# What are the design variables in Topology Optimization?

Many practitioners suggest keeping elements whose topology variable is in the range of 0.3 and 1.0, but do not explain the reasoning behind this suggestion.

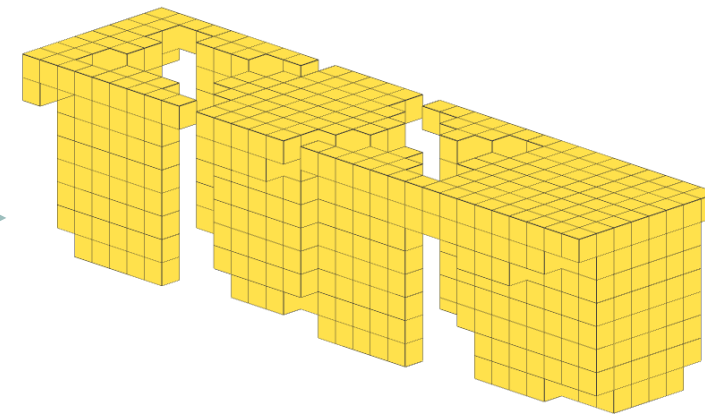
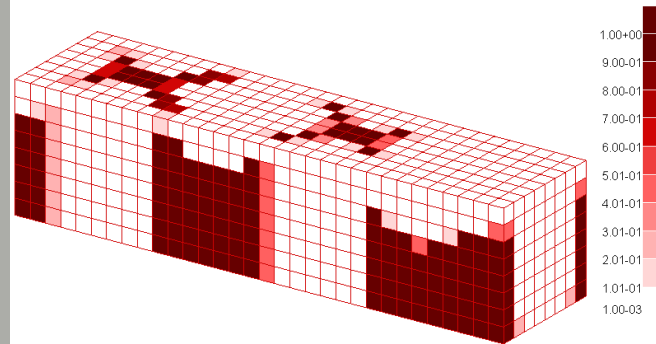
The following is an attempt to explain the suggestion.

Suppose the original stiffness of the material is  $E_0 = 200E9 \text{ Pa}$ .

- If  $x_i=0.3$ , then
  - $E_i = 200E9 \text{ Pa} * 0.3^3 = 5.4E9 \text{ Pa}$  (5.4 GPa)
  - A topology variable value of  $x_i=0.3$  yields a stiffness on the range of wood.
- If  $x_i=.0056$ , then
  - $E_i = 200E9 \text{ Pa} * .0056^3 = 3.5123E4 \text{ Pa}$  (35.123 kPa)
  - A topology variable value of  $x_i=.0056$  yields a stiffness on the range of gelatin dessert, such as Jello.

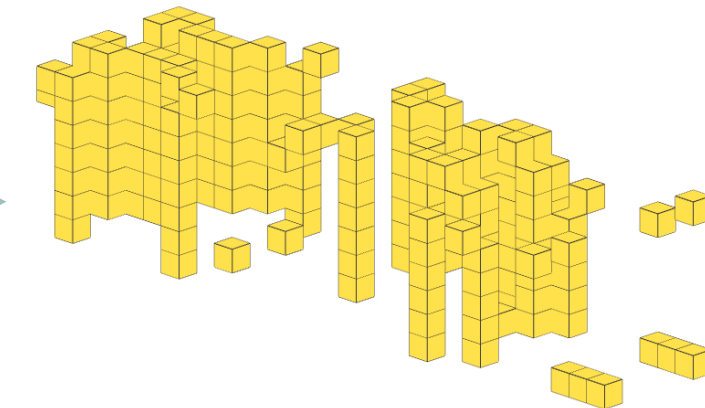
Elements with a stiffness equivalent to Jello are negligible and may be removed from the design. Elements with a stiffness equivalent to wood are also candidates for removal. Those who use topology optimization long enough will find the suggestion of keeping elements between 0.3 and 1.0 is not absolute. With trial and error, some will find that ranges of 0.5 to 1.0 or 0.4 to 1.0 will also sometimes work. Given that the best range is often unknown, this makes topology optimization a *black art*.

## Topology Optimization Results



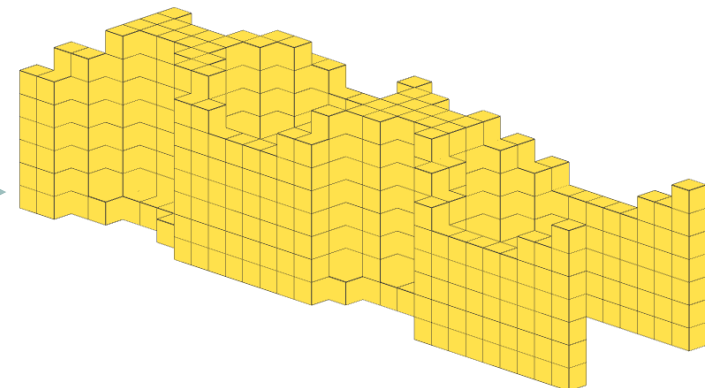
Elements in range:  
 $0 < x_i \leq .0056$   
 $0 < E_i \leq 3.5123E4 \text{ Pa}$   
Range: Jello

Do not keep



Elements in range:  
 $.0056 < x_i \leq 0.3$   
 $3.5123E4 < E_i \leq 5.4E9 \text{ Pa}$   
Range: Wood

Do not keep



Elements in range:  
 $0.3 < x_i \leq 1.0$   
 $5.4E9 \text{ Pa} < E_i \leq 200E9 \text{ Pa}$

Keep

# What is FRMASS or Fractional Mass?

Since the topology variables can range between 0 and 1, the final mass will be some fraction of the original mass. This is known as the fractional mass or FRMASS.

$$\text{FRMASS} = \frac{\sum p_i \cdot v_i}{\sum p_0 \cdot v_i}$$

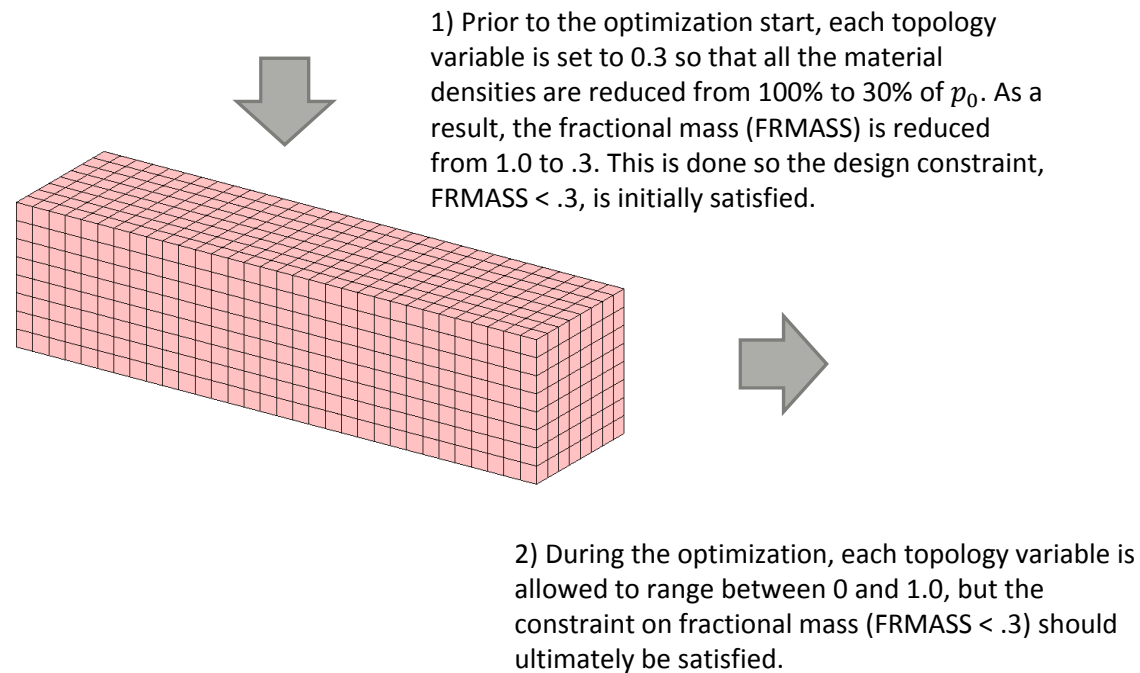
$p_0$  : The original material density

$p_i$  : The optimized material density of the element ( $p_i = p_0 \cdot x_i$ )

$v_i$  : Volume of element

0) Suppose this is the optimization problem statement:

- Objective: Minimize compliance
- Constraint: FRMASS < .3



# What is compliance?

Compliance is defined in many ways

- “Compliance is simply the product of the displacement times the applied load” (MSC Nastran Design Sensitivity and Optimization User’s Guide)
- For linear elastic solids, the work is twice the total strain energy

E L E M E N T   S T R A I N   E N E R G I E S				
ELEMENT-TYPE = HEXA		* TOTAL ENERGY OF ALL ELEMENTS IN PROBLEM	=	9.111034E+03
SUBCASE	1	* TOTAL ENERGY OF ALL ELEMENTS IN SET	-1 =	9.111034E+03
ELEMENT-ID	STRAIN-ENERGY	PERCENT OF TC	Total Strain Energy	
25	8.059148E+02	8.8455		
32	8.059148E+02	8.8455		6.447318E+03
33	8.059148E+02	8.8455		6.447318E+03
40	8.059148E+02	8.8455		6.447318E+03
TYPE = HEXA	SUBTOTAL	9.111034E+03	100.0000	

***** SUMMARY OF DESIGN CYCLE HISTORY *****				
(HARD CONVERGENCE ACHIEVED)				
NUMBER OF FINITE ELEMENT ANALYSES COMPLETED			56	
NUMBER OF OPTIMIZATIONS W.R.T. APPROXIMATE MODELS			55	
OBJECTIVE AND MAXIMUM CONSTRAINT HISTORY				
CYCLE NUMBER	OBJECTIVE FROM APPROXIMATE OPTIMIZATION	OBJECTIVE FROM EXACT ANALYSIS	FRACTIONAL ERROR OF APPROXIMATION	MAXIMUM VALUE OF CONSTRAINT
INITIAL		1.822207E+04		-4.625929E-15
1	5.076533E+03	1.321111E+04	6.163140E-01	9.999972E-09
2	5.721454E+03	1.120000E+04	4.893855E-01	6.604279E-09
3	4.220301E+03	1.016538E+04	-5.848357E-01	1.000032E-08
4	3.996396E+03	9.769504E+03	-5.909315E-01	9.983010E-09

# What is compliance? Continued

The .f06 file reports the value of compliance and strain energy. The following applies if and only if minimizing the compliance is the design objective.

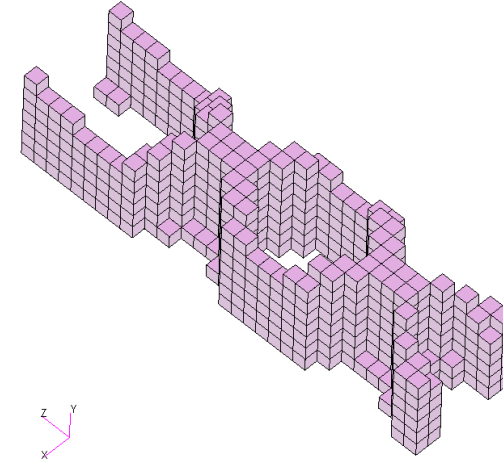
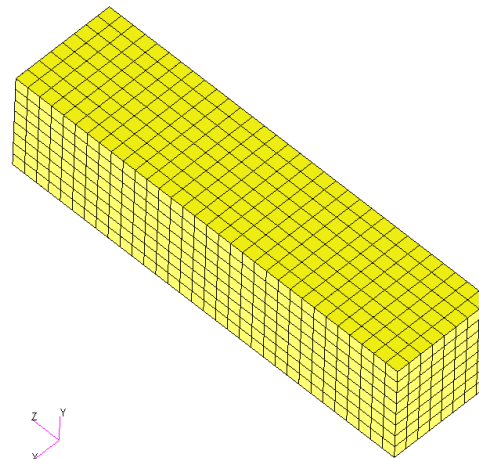
1. Make sure this statement is in the Case Control Section of the .bdf file.  
*ESE(THRESH=.99)=ALL*
2. Search the .f06 file for the initial design's  
*ELEMENT STRAIN ENERGIES*
3. Note the value of *TOTAL ENERGY OF ALL ELEMENTS IN PROBLEM*
4. Search the .f06 for the  
*SUMMARY OF DESIGN CYCLE HISTORY*
5. Note the value for OBJECTIVE FROM EXACT ANALYSIS for the INITIAL cycle number
6. The Compliance of 1.8222E4 is twice the TOTAL STRAIN ENERGY of 9.11E3.

ELEMENT STRAIN ENERGIES				
ELEMENT-TYPE = HEXA		* TOTAL ENERGY OF ALL ELEMENTS IN PROBLEM	=	9.111034E+03
SUBCASE 1		* TOTAL ENERGY OF ALL ELEMENTS IN SET	-1 =	9.111034E+03
	ELEMENT-ID	STRAIN-ENERGY	PERCENT OF TOTAL	STRAIN-ENERGY-DENSITY
	25	8.059148E+02	8.8455	6.447318E+03
	32	8.059148E+02	8.8455	6.447318E+03
	33	8.059148E+02	8.8455	6.447318E+03
	40	8.059148E+02	8.8455	6.447318E+03
TYPE = HEXA	SUBTOTAL	9.111034E+03	100.0000	

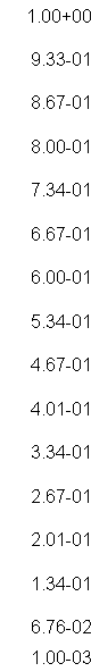
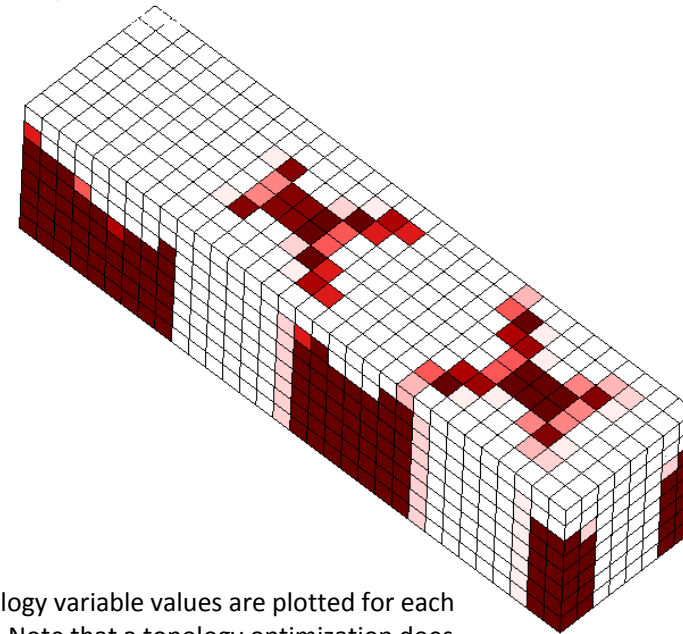
SUMMARY OF DESIGN CYCLE HISTORY				
(HARD CONVERGENCE ACHIEVED)				
NUMBER OF FINITE ELEMENT ANALYSES COMPLETED			56	
NUMBER OF OPTIMIZATIONS W.R.T. APPROXIMATE MODELS			55	
OBJECTIVE AND MAXIMUM CONSTRAINT HISTORY				
CYCLE NUMBER	OBJECTIVE FROM APPROXIMATE OPTIMIZATION	OBJECTIVE FROM EXACT ANALYSIS	FRACTIONAL ERROR OF APPROXIMATION	MAXIMUM VALUE OF CONSTRAINT
INITIAL		1.822207E+04		-4.625929E-15
1	5.076533E+03	1.323096E+04	-6.163140E-01	9.999972E-09
2	5.721454E+03	1.120504E+04	-4.893855E-01	6.604279E-09
3	4.220301E+03	1.016538E+04	-5.848357E-01	1.000032E-08
4	3.996396E+03	9.769504E+03	-5.909315E-01	9.983010E-09

# How can non-critical elements be removed from the design?

- Use the threshold to suppress non-critical elements
- The threshold means: *'Keep every element that has a topology variable value greater than the threshold'*
- Recall from before:
  - 0 - Topology variable values close to 0 are not critical to the design
  - 1 - Topology variable values close to 1 are critical to the design



The topology variable values are plotted for each element. Note that a topology optimization does not automatically remove elements. It is up to the user to manually decide which elements to keep.



Action:

Object:

Select Result Case

DESIGN CYCLE: 55, topex5a.des

Threshold

☐ Fringe

Target Entity

Entire Model

Group Name

HIGH\_DENS\_GRP4